Int J Life Cycle Assess (2014) 19:705–717
DOI 10.1007/s11367-013-0671-4

WOOD AND OTHER RENEWABLE RESOURCES

Life cycle assessment of fuel chip production from eucalypt forest residues

Ana Cláudia Dias

Received: 18 March 2013 / Accepted: 14 November 2013 / Published online: 22 November 2013

Abstract

Purpose Forest residues are becoming an increasingly important bioenergy feedstock. This study evaluates the environmental impacts associated with the production of fuel chips from eucalypt logging residues in Portugal, in order to identify the supply chains and machinery that bring the best environmental performance. Besides, the stages and operations with the largest environmental impact are identified.

Methods Life cycle assessment methodology is used starting with forest management up to delivery of chips to power plant. Three different configurations for logging residue processing were simulated as follows: roadside chipping of loose residues, terminal chipping of loose residues, and terminal chipping of bundled residues. In addition, the use of different equipment for tree felling and extraction of logging residue was considered. The default impact assessment methodology was the CML. In a sensitivity analysis, calculations were performed using characterization factors recommended by the International Reference Life Cycle Data System (ILCD). Different allocation criteria were tested for partitioning the environmental burdens between wood and forest residues produced during the stage of forest management.

Results and discussion Roadside chipping of loose residues seems to have less impacts regardless of the equipment used in tree felling and residue forwarding. However, for photochemical oxidant formation, this is not the case when trees are felled with a chainsaw when the CML methodology is applied. For the systems with terminal chipping, the better option will depend both on type of machinery used and distances traveled between the forest site and the power plant. The forest management stage has a relevant contribution to all the supply chains analyzed. Chipping and bundling have also important impacts, as well as forwarding when this operation is accomplished with a modified farm tractor. Moreover, transports have a significant impact when loose residues are chipped in a terminal.

Conclusions The choice of the allocation method between wood and residues affects significantly the absolute results, but it is irrelevant when the objective is to select the best supply chain configuration. The results obtained are valid for the input data considered, which rely on average values representative of the current most typical practices in Portugal. However, this methodology can also be applied as a decision supporting tool to select the supply chain with the best environmental performance on a case by case basis, using site-specific data.

Keywords Bioenergy · *Eucalyptus globulus* · Life cycle assessment (LCA) · Logging residues · Portugal

1 Introduction

In Portugal, forest biomass has been used as bioenergy source for several decades in forest-based industries to satisfy their energy requirements. The majority of this bioenergy is produced in combined heat and power (CHP) plants that mostly burn industrial by-products or wastes such as bark, sawdust, and shavings. Nowadays, there are nine CHP plants operating in the forest-based industries in Portugal with an installed capacity of about 360 MW that has been quite stable over the last decades (DGEG 2012; DGGE 2005; MEI 2007). Forest biomass is also burned in condensing power plants connected to the Portuguese electricity grid. The number of power plants has significantly increased over the last few

Responsible editor: Christian Bauer

A. C. Dias (✉)
Center for Environmental and Marine Studies (CESAM) &
Department of Environment and Planning, University of Aveiro,
3810-193 Aveiro, Portugal
e-mail: acdias@ua.pt

years from two power plants in 2006, with a total installed capacity of 12 MW, to ten power plants nowadays, with a total installed capacity of 106 MW (E2P 2012; DGEG 2012). In 2011, the electricity produced in these power plants accounted for about 1 % of the total electricity delivered in the national grid (DGEG 2012). This contribution is expected to increase in the near future with the construction of new power plants. According to the National Strategy for Energy, the target is to achieve an installed capacity of 250 MW by 2020 (Conselho de Ministros 2010). The power plants are fuelled mainly by logging residues composed of branches, foliage, and tops, but they also consume other forest residues such as stumps, wood from thinnings, and wood from burnt areas.

The more recent estimates of the amount of logging residues produced in Portugal range from 650 to 1,097 thousand tons (dry matter) per year (Dias and Azevedo 2004; Mateus 2007; Viana et al. 2010). However, the amount that can be technically and economically recovered is lower. Besides, there are also ecological restrictions, as logging residues play an important role in restoring the nutrients that have been removed from the soil during tree growth.

In Portugal, as in other countries, one of the main reasons for the development of policies stimulating bioenergy production from forest residues is climate change mitigation. However, there are other environmental impacts that should be taken into account in the assessment of the environmental sustainability of biofuels. This can be accomplished through the use of life cycle assessment (LCA) methodology. LCA has been applied to quantify the environmental impacts of bioenergy production chains based on forest resources (e.g., Bright and Strømman 2009; Butnar et al. 2010; Faix et al. 2010; Gasol et al. 2009; González-García et al. 2010, 2013; Pa et al. 2012; Roedl 2010), including also forest logging residues. However, only a few of the studies on forest logging residues have included several impact categories in the analysis (e.g., Johnson et al. 2012; Lindholm et al. 2010; Nuss et al. 2013) as most of them only focused on greenhouse gases and energy use (e.g., Forsberg 2000; Lindholm et al. 2011; Mckechnie et al. 2011; Valente et al. 2011a, b, 2012; Whittaker et al. 2011; Yoshioka et al. 2005). So far, no LCA study has been performed for eucalypt logging residues. Previous studies on eucalypt logging residues (Nunes 2008; Silva 2009) have been focused solely on greenhouse gas emissions and covered only part of the life cycle.

The objective of this study is to assess the environmental impacts resulting from the use of eucalypt (*Eucalyptus globulus* Labill.) logging residues as bioenergy feedstock in Portugal. Eucalypt logging residues are estimated to represent 47 to 58 % of the total logging residues available in Portugal (Dias and Azevedo 2004; Mateus 2007; Viana et al. 2010). Five supply chains representative of the most usual practices in the country are analyzed and compared. LCA methodology is applied from site preparation during forest management up to the delivery of chips to power plant.

2 Methods

2.1 Functional unit and system boundaries

The functional unit (FU) is the production of one oven dry ton (odt) of fuel chips of eucalypt logging residues delivered to the power plant. Oven dry weight was selected for the FU because moisture content may fluctuate typically between 15 and 55 % (CBE 2004). An average moisture content of 35 % was assumed. The average net calorific power of the chips is 15,500 MJ/odt (Núñez-Regueira et al. 2002).

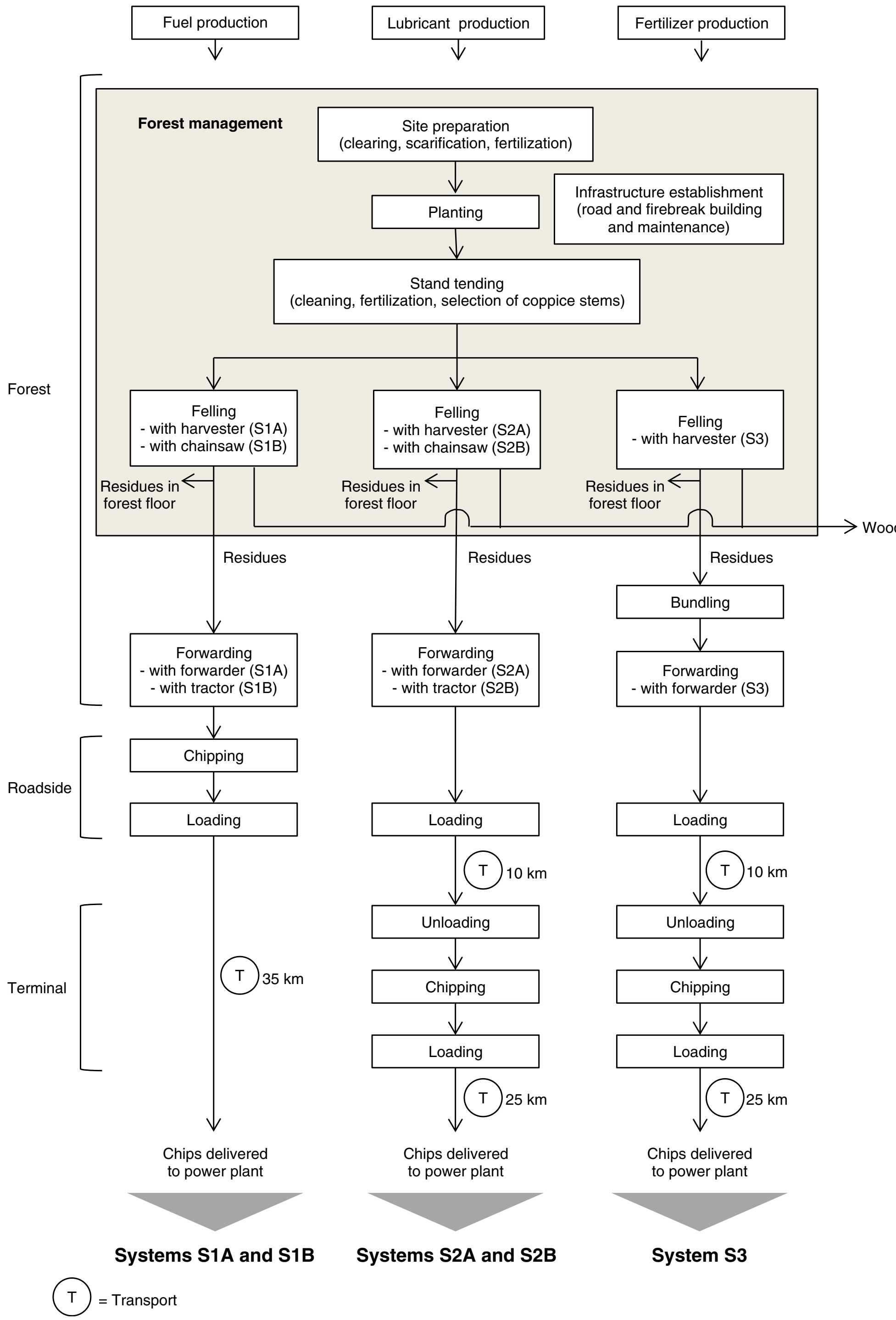
System boundaries, shown in Fig. 1, include the stage of forest management up to tree felling and the stages associated with logging residue collection (bundling and forwarding), chipping, and transport. Loading and unloading operations were included. The production of fuels, lubricants, and fertilizers consumed in all the stages was also considered. The transport of workers, machinery, and materials (fuels, lubricants, and fertilizers) was excluded, as well as the production of capital goods (buildings, machinery, and equipment).

2.2 System description

For the stage of forest management, all the operations carried out during infrastructure establishment, site preparation, planting, stand tending, and tree felling were considered. Eucalypt stands were assumed to be managed according to the high-intensity model described by Dias et al. (2007) and Dias and Arroja (2012), which relies on best management practices. According to this model, eucalypt stands are managed as coppiced stands in three successive rotations, each one with 12 years in length. Site preparation comprises undesirable vegetation clearing (by disking), soil scarification (ripping followed by subsoiling), and fertilizing (ternary fertilizer (15 % N, 12 % P_2O_5, 9 % K_2O) and superphosphate (21 % P_2O_5) applied together with subsoiling). Planting is a manual operation. Stand tending includes cleaning (by disking, eight times per revolution), fertilization (N-based fertilizer (30 % N) and ternary fertilizer (15 % N, 8 % P_2O_5, 8 % K_2O) are applied once per rotation), and selection of coppice stems (with chainsaw, once in the second and third rotations). The infrastructure establishment comprises road and firebreak building (once per revolution) and road and firebreak maintenance (six times per revolution).

Three different configurations for logging residue processing were analyzed as follows: (1) roadside chipping of loose residues, (2) terminal chipping of loose residues, and (3) terminal chipping of bundled residues. In addition, the use of different equipment for tree felling and extraction of logging residue was also simulated. In Portugal, tree felling is usually performed with harvester or chainsaw, and extraction could be accomplished with a forwarder or a farm tractor adapted to forest work. Harvesters and forwarders are mainly

Fig. 1 System boundaries



used when stands are managed by forest product industries or when large areas are harvested. It was assumed that harvesters are used in combination with forwarders, whereas chainsaws are used together with modified farm tractors. A total of five different chains were therefore evaluated as follows:

- System 1A (S1A): loose logging residues are chipped at the roadside; tree felling with harvester and residue extraction with forwarder
- System 1B (S1B): loose logging residues are chipped at the roadside; tree felling with chainsaw and residue extraction with modified farm tractor
- System 2A (S2A): loose logging residues are chipped at a terminal; tree felling with harvester and residue extraction with forwarder
- System 2B (S2B): loose logging residues are chipped at a terminal; tree felling with chainsaw and residue extraction with modified farm tractor

Table 1 Allocation factors for the forest management stage

Tree compartment	Output (odt)[a]	Allocation factor by mass (%)	Price (€/odt)	Allocation factor by price (%)	100 % allocation factor to wood (%)
Wood	1	75.3	83[b]	93.4[b]	100
Bark	0.137	10.0			0
Logging residues	0.133	10.3	35	4.6	0
Stumps	0.058	4.4	35	2.0	0

[a] Amount of biomass that leaves the forest over one revolution in relation to 1 odt of wood; 50 % of the logging residues and stumps are assumed to be left in the forest floor

[b] Price and allocation factor for wood with bark

– System 3 (S3): logging residues in bundles are chipped at a terminal; tree felling with harvester and residue extraction with forwarder

Table 2 Inventory data for the forest management operations up to felling associated with the production of 1 odt of eucalypt wood, using alternative machinery for felling

	Felling with harvester	Felling with chainsaw
Inputs:		
Diesel (L)	4.84	2.73
Petrol (L)	0.095	0.780
Lubricants (L)	0.245	0.163
Superphosphate (g)	960	960
Ternary fertilizer 1 (g)[a]	172	172
Ternary fertilizer 2 (g)[b]	3,787	3,787
N-based fertilizer (g)	2,273	2,273
Outputs:		
Products:		
Wood (odt)	1	1
Bark (odt)	0.137	0.137
Logging residues (odt)	0.133	0.133
Stumps (odt)	0.058	0.058
Air emissions:		
CO_2 (g)	13,205	9,143
CH_4 (g)	0.286	1.32
N_2O (g)	21.0	20.7
SO_2 (g)	8.22	4.65
CO (g)	74.7	369
NH_3 (g)	158	158
NO_x (g)	120	69.1
Water emissions:		
NO_3^- (g)	1,725	1,725
P (g)	5.50	5.50
Residues left in the forest floor:		
Logging residues (odt)	0.133	0.133
Stumps (odt)	0.058	0.058

[a] 15 % N, 12 % P_2O_5, 9 % K_2O

[b] 15 % N, 8 % P_2O_5, 8 % K_2O

In the systems S1A and S1B, loose residues are collected, respectively, with a forwarder and a modified farm tractor, and chipping takes place at the roadside using a mobile chipper. The chips are then loaded onto trucks and transported to the power plant.

In the systems S2A and S2B, loose residues are also collected, respectively, with a forwarder and a modified farm tractor, and then are transported, normally by tractors with a semitrailer, to a terminal located near the forest (by preference, not more than 15 km). After chipping at the terminal, the chips are transported to the power plant by truck.

In the system S3, residues are bundled into cylindrical bales in the clear cut area with a bundler attachment mounted on a forwarder. Bundles are forwarded to the roadside with a forwarder and transported to a terminal by truck. Chipping takes place at the terminal before transport of chips to the power plant by truck.

2.3 Allocation

The stage of forest management is a multifunctional process as both wood for the wood-based industry and residues for bioenergy (logging residues, bark, and stumps) are produced. In this study, a mass allocation is applied to allocate the environmental burdens to wood and residues that leave the forest, in accordance with Valente et al (2011a) and Whittaker et al. (2011). No environmental burden was allocated to the residues that are left in the forest floor. Table 1 shows the mass allocation factors considered. The relative proportion of each tree compartment (wood, bark, logging residues, and stumps) was taken from Tomé et al. (2006). According to CBE (2004), the amount of forest residues collected may vary between 5 and 95 % of the total amount produced. This percentage depends not only on ecological reasons but also on technical and logistic restrictions. In this study, half of the logging forest residues and stumps were assumed to be left in the forest floor.

2.4 Inventory analysis

2.4.1 Forest management operations

The inventory data for the production (up to felling) of one odt of eucalypt wood are shown in Table 2. These data were estimated using the methodology and data described by Dias and Arroja (2012) for a typical wood productivity (under bark) of 10 m^3 wood ha^{-1} $year^{-1}$. The FU considered by these authors was 1 m^3 of wood under bark. Thus, to convert the data to the current FU, a basic density of 0.550 odt m^{-3} of wood was adopted (Valente et al. 1992).

Carbon dioxide (CO_2) absorbed from the atmosphere during forest growth was assumed to be released back to the atmosphere during the oxidation of wood and forest residues in the forest floor and along the downstream life cycle stages of these materials.

2.4.2 Collection and chipping of forest residues

Table 3 presents the inventory data for the operations associated with logging residue collection and chipping.

The amounts of diesel consumed in the operations were calculated based on the effective work time needed to perform each operation and the respective fuel consumption per hour of machine work. Data for these parameters were retrieved from field measurements performed by CBE (2008, 2004), Dias et al. (2007) and Silva (2009). The amount of lubricants used in the machinery was assumed to be 5 % of the amount of diesel consumed in the machine (Athanassiadis et al. 1999; Klvac et al. 2003). Air emissions from fuel combustion were calculated based on emission factors from EEA (2009).

Dry matter losses of 2 % were considered both for residue storage and chipping (Forsberg 2000; Whittaker et al. 2011).

2.4.3 Transport

The type of transport used in the different systems and the distances traveled are shown in Table 4. Optimal distances from an economic point of view were considered based on Viana et al. (2010) and Silva (2009). Empty return was considered for each transport stage. Inventory data were taken from the Ecoinvent database (Ecoinvent 2010).

2.4.4 Fuel, lubricant, and fertilizer production

Inventory data for the production of fuels (diesel and petrol), lubricants, and fertilizers were sourced from the Ecoinvent database (Ecoinvent 2010)[1].

[1] Diesel, at regional storage/RER; petrol, two-stroke blend, at regional storage/RER; lubricating oil, at plant/RER; ammonium sulphate, as N, at regional storehouse/RER; triple superphosphate, as P_2O_5, at regional storehouse/RER; potassium chloride, as K_2O, at regional storehouse/RER.

2.5 Impact assessment

Characterization factors from CML (Guinèe et al. 2001) were applied since this impact assessment method is widely used in European countries. The impact categories selected for the analysis were those for which enough inventory data were available, namely abiotic resource depletion, global warming, photochemical oxidant formation, acidification, and eutrophication.

3 Results and discussion

Table 5 and Fig. 2 present the impact assessment results obtained for the production of one odt of chips from eucalypt logging residues.

For all the impact categories analyzed, other than photochemical oxidant formation, S1A is the system with the less impact followed, in this order, by S1B, S2A, S3, and S2B. This means that roadside chipping of loose residues (S1A and S1B) is the option with smaller impacts regardless of the equipment used in tree felling and residue forwarding due to a lower diesel requirement in transport and loading/unloading operations when compared to terminal chipping of loose residues (S2A and S2B). On its turn, terminal chipping of loose residues has less impact than the bundling system (S3) if harvester and forwarder are used instead of chainsaw and modified farm tractor for felling and forwarding operations. In the bundling system (S3), the impacts related with forwarding and transport are smaller than in S2A (system that employs the same forwarding equipment and place of chipping). However, the impacts of the additional operation of bundling are higher than this impact reduction associated with forwarding and transport. It should be noted that the differences between the impacts of S2A, S2B, and S3 are small.

For all the impact categories, the combined use of harvester and forwarder (typically applied in the forest managed by the forest product industry) has less impact than the combined use of chainsaw and modified farm tractor (more traditional machinery). The use of forwarders instead of modified farm tractors leads to much smaller impacts due to the higher load capacity of forwarders. Contrastingly, the use of harvesters originates higher impacts than chainsaws, although this difference is not as important as in the case of forwarding machinery. The only exception is the impact category of photochemical oxidant formation where the impact of chainsaw exceeds that from harvester mainly because the carbon monoxide (CO) emission factor of the chainsaw (309 g CO/odt of wood felled) is much higher than the CO emission factor of the harvester (14 g CO/odt of wood felled). These CO emission factors were calculated based on the values considered by Dias and Arroja (2012) for the CO emission factor per unit mass of each fuel (diesel in harvester and petrol in

Table 3 Inventory data for the operations undertaken during forest residue collection and chipping

	Loose logging residues				Logging residues in bundles					
	Forwarding		Loading or unloading of loose residues	Chipping[a]	Loading of chips	Bundling	Forwarding	Loading or unloading of bundles	Chipping[a]	Loading of chips
	Forwarder	Tractor								
Inputs:										
Diesel (L)	1.92	4.44	0.462	3.94	0.498	3.42	1.32	0.462	3.89	0.498
Lubricants (L)	0.0960	0.222	0.0231	0.197	0.0249	0.171	0.066	0.0231	0.194	0.0249
Outputs:										
Logging residues (odt)	1	1	1			1	1	1		
Chips (odt)				1	1				1	1
Air emissions:										
CO_2 (g)	5,150	11,900	1,240	10,620	1,340	9,200	3,540	1,240	10,460	1,340
CH_4 (g)	0.0538	0.124	0.0129	0.111	0.0140	0.0960	0.0370	0.0129	0.109	0.0140
N_2O (g)	0.225	0.520	0.054	0.463	0.0585	0.402	0.155	0.054	0.456	0.0585
SO_2 (g)	3.26	7.54	0.785	6.72	0.848	5.82	2.24	0.785	6.62	0.848
CO (g)	12.8	29.5	3.07	26.3	3.32	22.8	8.77	3.07	25.9	3.32
NH_3 (g)	0.0130	0.0302	0.00314	0.0269	0.00339	0.0233	0.00896	0.00314	0.0265	0.00339
NO_x (g)	47.4	110	11.4	97.7	12.3	84.7	32.6	11.4	96.3	12.3

[a] Chipping operation includes also residue feeding to the chipper

Table 4 Transport profile

System	Material	Distance (km)[a]	Transport mode
S1A, S1B	Chips from roadside to power plant	35	Truck 40 t, payload 20 t[b]
S2A, S2B	Loose residues from roadside to terminal	10	Tractor with semi-trailer, payload 10 t[c]
S2A, S2B	Chips from terminal to power plant	25	Truck 40 t, payload 20 t[b]
S3	Bundles from roadside to terminal	10	Truck 40 t, payload 24 t[d]
S3	Chips from terminal to power plant	25	Truck 40 t, payload 20 t[b]

[a] This distance corresponds to an outward journey. A round trip with an empty return journey was considered in the calculations

[b] Impacts modeled based on the Ecoinvent process “operation, lorry >28 t, fleet average/CH” with a payload of 20 t

[c] Adapted from the Ecoinvent process “transport, tractor and trailer/CH” by changing the payload from 16 to 10 t

[d] Impacts modeled based on the Ecoinvent process “operation, lorry >28 t, fleet average/CH” with a payload of 24 t

chainsaw), and for the effective work time and hourly fuel consumption of both machines. This difference in the CO emissions is the main cause of the largest values obtained for photochemical oxidant formation in S1B and S2B. The trend obtained for the other impact categories is also observed for photochemical oxidant formation when harvester and forwarder are used, i.e., S1A<S2A<S3.

Studies performed for Sweden (Eriksson and Gustavsson 2008; Lindholm et al. 2010) and Finland (Wihersaari 2005) also concluded that the bundling system seems to generate higher impacts than the systems where loose residues are collected. A Portuguese study (Silva 2009) found that the bundling system has similar greenhouse gas emissions as the system with terminal chipping. However, according to Eriksson and Gustavsson (2008), the bundling system has lower costs. This system has also logistic advantages because residue compression allows the transport of higher amounts of residues per trip compared with the other systems and, besides, bundles can be transported with conventional log trucks. Besides, bundling makes storage easy as uncomminuted residue does not decay as fast as chips, and therefore can be stored for extended periods without risking heavy dry matter losses (Cuchet et al. 2004).

As in the present study, the results obtained by Silva (2009) and Wihersaari (2005) for chips from loose residues show that the greenhouse gas emissions over the chip production chain are larger for systems with terminal chipping than for systems with roadside chipping. However, it should be noted that terminal chipping is necessary in some specific cases when roadside chipping is unfeasible (e.g., when there is not enough space to install a chipper or working conditions are difficult) or is not economically viable (e.g., due to small amounts of residues). Moreover, terminal chipping has other advantages because terminals operate as a buffer storage, which enables a more secure supply of fuel chips, higher flexibility, and better fuel quality (Johansson et al. 2006; Laitila 2008). These advantages apply not only for systems based on loose residues but also for bundling systems.

Forest management is the stage with the largest contribution to all the systems analyzed regardless of the impact category (Fig. 2). The great importance of the forest management stage is mostly associated with fossil fuel (diesel and petrol) combustion in motor–manual and mechanized operations for the impact categories of photochemical oxidant formation and global warming. For the global warming impact category, nitrous oxide emissions resulting from fertilizer application are also important, accounting for about 25 % of the total global warming impact of the forest management stage. For the eutrophication and acidification impact categories, the role of emissions derived from fertilizing is even higher, being around 95 and 70 % of the total impact of the forest management stage, respectively. In the case of abiotic resource depletion, phosphorus depletion derived from fertilizer production is also very relevant. For these reasons, the

Table 5 Impact assessment results associated with the production of 1 odt of chips

	System				
	S1A	S1B	S2A	S2B	S3
Abiotic resource depletion (kg Sb-eq)	2.11×10^{-5}	2.19×10^{-5}	2.26×10^{-5}	2.34×10^{-5}	2.31×10^{-5}
Global warming (kg CO_2-eq)	46.2	50.6	55.6	60.0	57.9
Photochemical oxidant formation (kg C_2H_4-eq)	1.44×10^{-2}	2.24×10^{-2}	1.64×10^{-2}	2.44×10^{-2}	1.91×10^{-2}
Acidification (kg SO_2-eq)	0.457	0.479	0.522	0.543	0.531
Eutrophication (kg PO_4^{3-} -eq)	0.260	0.264	0.274	0.278	0.274

stage of forest management contributes even more to the total impact of the systems than in the other impact categories, representing 80–88, 50–65, and 69–79 % of the total eutrophication, acidification, and abiotic depletion potentials, respectively.

Valente et al. (2011a) and Whittaker et al. (2011) have also considered the stage of forest management in their LCA studies of chips produced from logging residues of tree species growing in Norway and the UK, respectively, collected in bundles. The contribution of this stage to global warming was about 20 % for Valente et al. (2011a) and 30 % for Whittaker et al. (2011). The latter percentage is similar to the one obtained in this study (35 %), although Whittaker et al. (2011) have included the manufacture and maintenance of machinery, which was excluded in this study. The global warming potential is also similar in Whittaker et al. (2011) (64 kg CO_2-eq/odt) and in this study (58 kg CO_2-eq/odt), despite differences in system boundaries and allocation factors, among others.

Regarding the operations taking place from tree felling onwards, the most relevant to all the impact categories are the following: chipping for all the systems, forwarding when modified farm tractor is used (S1B and S2B), transports when loose residues are chipped in a terminal (S2A and S2B), and bundling (S3). The impacts of these operations arise mostly from diesel combustion. Other authors also pointed out chipping and transports as the major hotspots in fuel chip production chains (Eriksson and Gustavsson 2008; Johnson et al. 2012; Lindholm et al. 2010; Silva 2009; Valente et al. 2011a; Whittaker et al. 2011).

The global warming potential obtained for the operations taking place after tree felling is 26 and 34 kg CO_2-eq/odt for roadside chipping systems (S1A and S1B, respectively), 35 and 44 kg CO_2-eq/odt for terminal chipping of loose residues systems (S2A and S2B, respectively), and 38 kg CO_2-eq/odt for the bundling system (S3). The results found by Silva (2009) for logging residues in Portugal are similar: 28 kg CO_2-eq/odt for roadside chipping and 38 kg CO_2-eq/odt both for terminal chipping of loose residues and bundling systems (considering moisture content of 35 % for chips). The results reported by Nunes (2008) for eucalypt logging residues in Portugal also fit well with the results obtained in this study: 30–34 kg CO_2-eq/odt for roadside chipping systems (considering moisture content of 35 % for chips). For Sweden, Lindholm et al. (2010) reported 36 kg CO_2-eq/odt for roadside chipping, 60 kg CO_2-eq/odt for terminal chipping of loose residues, and 67 kg CO_2-eq/odt for bundling systems. The results obtained for terminal chipping and bundling systems are higher than those calculated in the current study, which may be mainly explained by the largest transport distances in Sweden (130–136 km against 35 km in Portugal). For eutrophication, these authors presented results varying between 29 and 54 g PO_4^{3-}-eq/odt that fall in the same range of those obtained here (32–56 g PO_4^{3-}-eq/odt). The same is true for acidification in the case of roadside and terminal chipping of loose residues: 163–269 g SO_2-eq/odt in Lindholm et al.

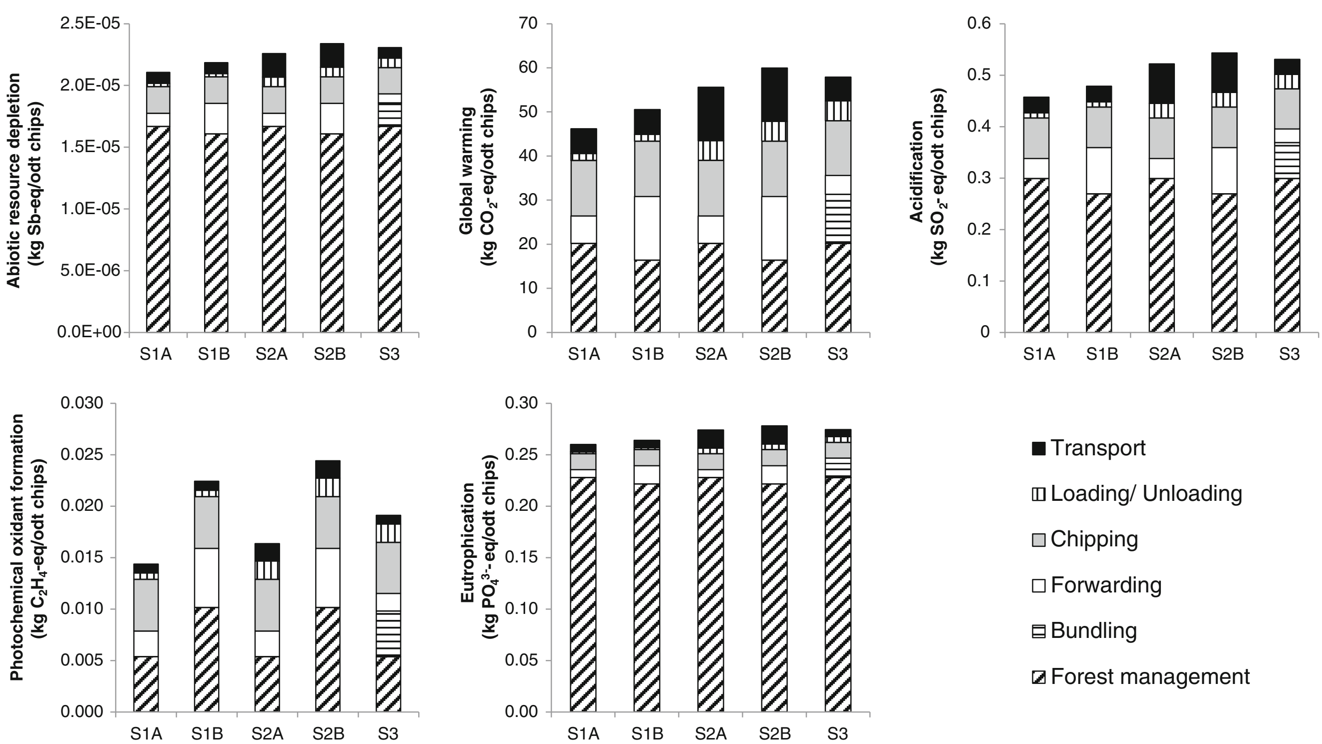


Fig. 2 Impact assessment results using the default impact assessment methodology (*CML*)

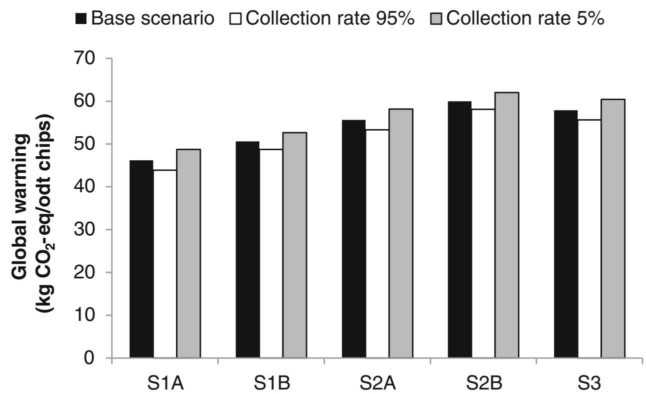


Fig. 4 Results of the sensitivity analysis for the global warming impact category: effect of changing the collection rate of logging residues

(2010) and 158–274 g SO_2-eq/odt in this study. For the bundling system, the result reported by Lindholm et al. (2010) (307 g SO_2-eq/odt) is higher than the one obtained in the current study (232 g SO_2-eq/odt). For a representative forest stand in the Inland West region of the United States, Johnson et al. (2012) estimated about 50 kg CO_2-eq/odt for roadside chipping of logging residues and about 95 kg CO_2-eq/odt for terminal chipping of loose logging residues, which are much higher than the results of the current study, but the transport distances are also higher (145 km). It should be noted that a direct comparison with the absolute impacts obtained in earlier studies may be not completely correct due to the consideration of different methodological aspects (e.g., boundary, functional unit, and impact assessment methodology). Therefore, the comparisons above should be considered with caution.

Four sensitivity analyses were carried out to evaluate the influence of data and methodological assumptions in the results. First, the effect of changing the distances traveled in each system was evaluated in relation to the base scenario that considers optimal distances. Since real ranges of distance variation are not available, in this sensitivity analysis, the distances were increased and decreased by 50 %. Figure 3 illustrates the results obtained for the global warming impact category, which show the same trend as the results obtained for the remaining impact categories. The systems where transports are more significant (S2A and S2B) are the most affected by these changes. When distances are increased by 50 %, roadside chipping systems (S1A and S1B) still have less impact, but the bundling system (S3) becomes a better option than terminal chipping of loose residues (S2A and S2B). When distances are decreased by 50 %, roadside chipping systems remain with the smallest impact, but the bundling system has more impact than the terminal chipping of loose residues systems.

Figure 4 shows the results of a sensitivity analysis where the collection rate of logging residues was changed from 50 to 5 and 95 %, the range found in the field by CBE (2004). The example of the global warming impact category is presented and the results obtained for the other impact categories show the same trend. The change in the residue collection rate affects only slightly the results (less than 6 %). When the collection rate increases from 50 to 95 %, the output of logging residues from the forest management stage increases from 0.133 to 0.252 odt per odt of wood and, consequently, the impacts associated with the production of 1 odt of chips decrease as less forest area is needed. At the same time, the mass allocation factor to logging residues increases from 10.3 to 16.8 %, counteracting the impact decrease mentioned above. For the collection rate of 5 %, the reduction in the output of logging residues from the forest management stage to 0.013 odt per odt of wood leads to more impacts from this stage to produce 1 odt of chips but, in opposition, the mass allocation factor to logging residues decreases to 1.1 %.

Thirdly, a sensitivity analysis concerning alternative allocation criteria was performed. Economic allocation was simulated using the allocation factors presented in Table 1. They were calculated based on current average prices of eucalypt biomass in Portugal (AFLOBEI 2012; GERA 2012). Allocation of all the burdens to wood was also tested as this procedure is adopted in several studies. In this case, the forest management stage is excluded as forestry activities are not

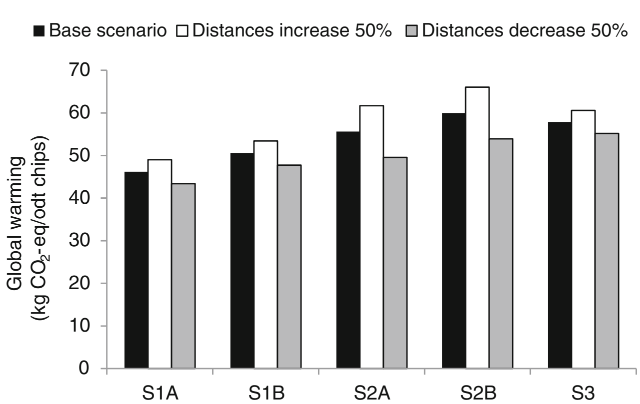


Fig. 3 Results of the sensitivity analysis for the global warming impact category: effect of changing the distances traveled

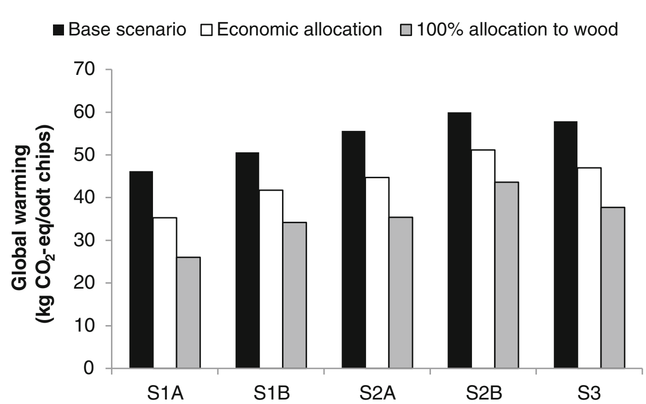


Fig. 5 Results of the sensitivity analysis for the global warming impact category: effect of changing the allocation criteria

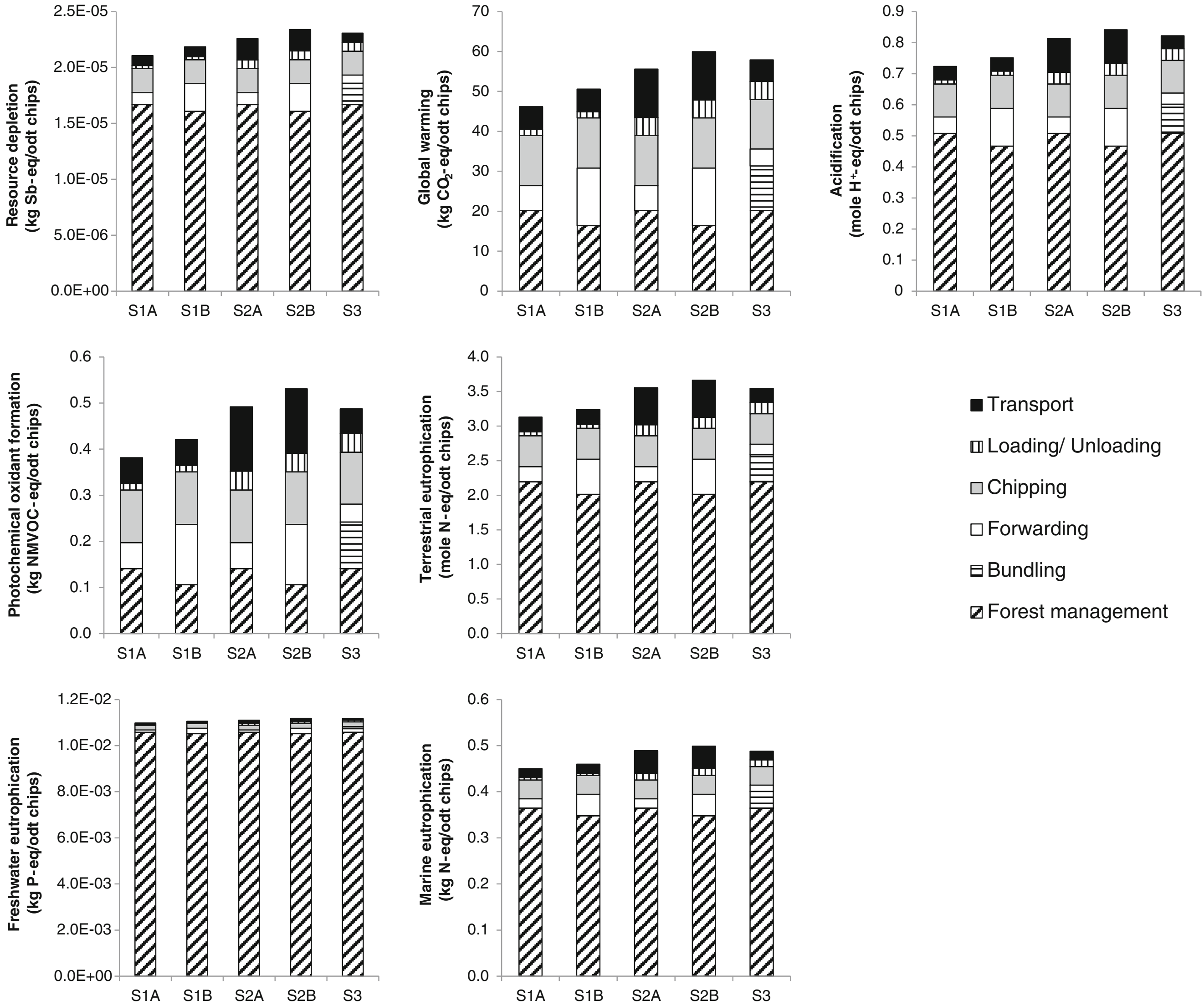


Fig. 6 Results of the sensitivity analysis: effect of changing the impact assessment methodology. Impact assessment results using the characterization factors recommended by the ILCD

influenced by the existence of a downstream bioenergy system (Forsberg 2000; Yoshioka et al. 2005). The results obtained for global warming are illustrated in Fig. 5 as an example, as they show the same trends of the remaining impact categories. Compared to the mass allocation, the economic allocation leads to smaller impacts because the allocation factor to logging residues decreases from 10.3 to 4.6 %. The reduction in the total impacts in relation to the base scenario varies between 12 % in abiotic resource depletion and 47 % in eutrophication. The impact reduction is even higher when 100 % of the environmental impacts are allocated to wood, ranging from 22 % in abiotic resource depletion to 88 % in eutrophication.

Finally, the effects of using a different impact assessment methodology are illustrated in Fig. 6, which presents the results obtained with characterization factors recommended by the International Reference Life Cycle Data System (ILCD) (EC 2012). The results obtained for global warming and resource depletion are exactly the same of the base scenario as the characterization factors are taken from IPCC (2007) and van Oers et al. (2002), respectively, in both methodologies. For the remaining impact categories, the absolute results obtained with the ILCD methodology are not directly comparable with those obtained with the CML methodology applied in the base scenario due to differences in the category indicators. Besides, eutrophication is divided into terrestrial, freshwater, and marine eutrophication in the ILCD methodology. Despite these differences, the analyzed systems present the same ranking using one methodology or the other, except for the impact category of photochemical oxidant formation. In fact, the results obtained with the ILCD methodology for the five systems show the same trend evidenced by the CML methodology for the impact categories other than photochemical oxidant formation, i.e., S1A<S1B<S2A<S3<S2B. For

the photochemical oxidant formation, this trend is valid except for the results obtained in S2B, which are slightly higher than those obtained in S3. Besides, contrary to what happens with the CML methodology, the use of chainsaw generates smaller impact than harvesters for tree felling because the characterization factor of CO in the ILCD methodology is much smaller than the characterization factor of nitrogen oxides (NO_x) (0.0456 and 1 kg NMVOC-eq/kg, respectively). In the CML methodology, the characterization factors of these gases are similar (0.027 kg C_2H_4-eq/kg for CO and 0.028 kg C_2H_4-eq/kg for NO_x). With the ILCD methodology, forest management is still the stage that presents the largest contribution to the systems analyzed. The only exceptions are the systems S1B and S2B in the impact category of photochemical oxidant formation. The most relevant operations occurring from tree felling onwards are also the same with both impact assessment methodologies.

The results obtained in this study for the impacts associated with the production of fuel chips should be looked as average results representative of the current most typical practices in Portugal. The sensitivity analyses performed demonstrate that they are affected by uncertainty due to normative choices (e.g., allocation, impact assessment methodology) and to parameter uncertainty and variability (e.g., traveled distances, residue collection rates). Dias and Arroja (2012) also corroborate that the impacts from the eucalypt forest management stage may vary widely depending on forest management intensity and on biomass productivity. Besides, the results obtained in the current study are also affected by model uncertainty because the calculation model may not fully capture real processes. For example, the forest management model adopted in this study assumes a certain type and number of forest operations that comply with the best practices recommended for eucalypt stands in Portugal. In practice, the best management practices are not applied over the entire forest area. Besides, the forest management model used in this study considers a high mechanization level for the operations, which in practice is not always feasible, namely in very declivitous or stony sites, where operations have to be carried out manually. More accurate results could be obtained when the exact provenance of the logging residues and the location of the terminal and power plant are known. In this case, site-specific data on forest management practices, logging residue production and collection rates, transport profiles, among others, should be adopted. Besides, most of the data on fuel consumption for the operations of forest management, residue collection, and chipping were based on field measurements, but the corresponding emissions were estimated using generic emission factors retrieved from the literature. Therefore, more robust results could be obtained provided that machinery-specific emission factors become available.

This study addresses five impact categories, namely abiotic resource depletion, global warming, photochemical oxidant formation, acidification, and eutrophication. Other impact categories, such as ozone layer depletion and human toxicity, usually considered in LCA studies, but not very often in LCA studies focused on forest residues valorization, were not addressed due to the lack of inventory data for the foreground system. Impacts arising from land use and water use were also excluded due to the lack of widely accepted impact assessment methodologies (Kounina et al. 2013; Mattila et al. 2012), although they could be relevant for systems that comprise forestry activities.

This study assumes that biogenic CO_2 is neutral, but further research is required to obtain a more accurate CO_2 balance, since carbon stocks in soil are expected to vary with logging residue removal and, besides, regrowth of eucalypt plantations will take about 12 years, while CO_2 emission to the atmosphere from chips burning will occur immediately. Further research is also needed to analyze the effects of removing logging residues on biodiversity and soil fertility.

4 Conclusions

This study assesses some of the environmental impacts of producing fuel chips from eucalypt logging residues in Portugal. Moreover, it identifies the operations with the largest environmental impact. This analysis is particularly important given, on one side, the immaturity of the forest residue market in Portugal and the increasing demand of forest residues for bioenergy on the other side.

The results underline the fact that the environmental impacts are influenced both by the type of machinery used for tree logging and residue forwarding and by the supply chain configuration. The use of chainsaw instead of harvester for tree felling leads to smaller environmental impacts. However, for the impact category of photochemical oxidant formation, the results are divergent when the CML methodology is selected. The use of forwarders for residue forwarding originates less impact than modified farm tractors. The smallest impact was obtained for the supply chains with roadside chipping. For the systems with terminal chipping, the better option will depend not only of the machinery used but also on the distance between the forest and the power plant.

The criteria adopted for allocating the environmental impacts of the forest management stage between wood and residues affects significantly the results in absolute terms. However, the allocation criteria are irrelevant when the objective is to determine in relative terms what is the best supply chain configuration.

It should be noted that the results obtained in this study are valid for the input data considered, which rely on average values representative of the current most typical practices in Portugal. The methodology adopted here could also be applied as a decision supporting tool to predict what is the supply

chain with the least environmental impact on a case by case basis, using site-specific data.

Acknowledgments This study has been supported by the project ECOTECH SUDOE—International Network on LCA and Ecodesign for Eco-innovation (SOE2/P2/E377) funded by the EU Interreg IV B Sudoe Programme. Thanks are also due to FCT (Science and Technology Foundation; Portugal) for the scholarship granted to Ana Cláudia Dias (SFRH/BPD/75788/2011). The author also expresses her gratitude to Luis Arroja (CESAM/DAO—University of Aveiro) for supervising her work and constructive comments.

References

AFLOBEI (2012) Preços indicativos dos produtos florestais. Folha Florestal 25:4

Athanassiadis D, Lidestav G, Wästerlund I (1999) Fuel, hydraulic oil and lubricant consumption in Swedish mechanized harvesting operations, 1996. J For Eng 10:59–66

Bright RM, Strømman AH (2009) Life cycle assessment of second generation bioethanols produced from Scandinavian boreal forest resources. A regional analysis for Middle Norway. J Ind Ecol 13:514–531

Butnar I, Rodrigo J, Gasol CM, Castells F (2010) Life-cycle assessment of electricity from biomass: case studies of two biocrops in Spain. Biomass Bioenergy 34:1780–1788

CBE (2004) Optimização das operações de exploração florestal, recolha, acondicionamento, transporte e transformação primária da biomassa florestal residual para a produção de energia. Centro da Biomassa para a Energia, Miranda do Corvo

CBE (2008) Utilização da biomassa florestal residual para aproveitamento energético. Centro da Biomassa para a Energia, Miranda do Corvo

Conselho de Ministros (2010) Resolução do Conselho de Ministros no 29/2010. Diário da República, 1.ª série, No. 73:1289-1296

Cuchet E, Roux P, Spinelli R (2004) Performance of a logging residue bundler in the temperate forest of France. Biomass Bioenergy 27: 31–39

DGEG (2012) Renováveis estatísticas rápidas nº 90. Direcção Geral de Energia e Geologia, Lisbon

DGGE (2005) Renováveis estatísticas rápidas no. 10. Direcção Geral de Geologia e Energia, Lisbon

Dias AC, Arroja L (2012) Environmental impacts of eucalypt and maritime pine wood production in Portugal. J Clean Prod 37:368–376

Dias J, Azevedo JLT (2004) Evaluation of biomass residuals in Portugal Mainland. In: Afgan NH, Carvalho MDG (eds) International conference on new and renewable energy technologies for sustainable development, Ponta Delgada, pp 214-228

Dias AC, Arroja L, Capela I (2007) Carbon dioxide emissions from forest operations in Portuguese eucalypt and maritime pine stands. Scand J For Res 22:422–432

E2P (2012) Energias endógenas de Portugal – base de dados de fontes renováveis de energia. http://e2p.inegi.up.pt/index.asp. Accessed 17 December 2012

EC (2012) Characterisation factors of the ILCD recommended life cycle impact assessment methods. Database and supporting information. European Commission, Joint Research Centre, Institute for Environment and Sustainability, Luxembourg

Ecoinvent (2010) Ecoinvent database v 2.2. Swiss Centre for Life Cycle Inventories, Dübendorf

EEA (2009) EMEP/EEA air pollutant emission inventory guidebook 2009. EEA Technical Report 9/2009. European Environment Agency, Copenhagen

Eriksson LN, Gustavsson L (2008) Biofuels from stumps and small roundwood—costs and CO_2 benefits. Biomass Bioenergy 32:897–902

Faix A, Schweinle J, Schöll S, Becker G, Meier D (2010) (GTI-tcbiomass) Life-cycle assessment of the BTO®-process (biomass-to-oil) with combined heat and power generation. Environ Prog Sustain Energy 29:193–202

Forsberg G (2000) Biomass energy transport—analysis of bioenergy transport chains using life cycle inventory method. Biomass Bioenergy 19:17–30

Gasol CM, Gabarrell X, Anton A, Rigola M, Carrasco J, Ciria P, Rieradevall J (2009) LCA of poplar bioenergy system compared with *Brassica carinata* energy crop and natural gas in regional scenario. Biomass Bioenergy 33:119–129

GERA (2012) Preços de produtos florestais. GERA—Gestão Rural Activa. http://www.gera.com.pt/. Accessed 3 December 2012

González-García S, Gasol CM, Gabarrell X, Rieradevall J, Moreira MT, Feijoo G (2010) Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe. Renew Energy 35:1014–1023

González-García S, Mola-Yudego B, Murphy RJ (2013) Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. Int J Life Cycle Assess 18:783–795

Guinèe J, Gorree M, Heijungs R, Huppes G, Kleijn R, de Koning A, van Oers L, Weneger A, Suh S, Udo de Haes H, de Bruin H, Duin R, Huijbregts M (2001) Life cycle assessment: an operational guide to the ISO standards. Ministry of Housing, Spatial Planning and the Environment and Centre of Environmental Science / Leiden University, Leiden

IPCC (2007) IPCC fourth assessment report: climate change 2007—the physical science basis. Cambridge University Press, Cambridge and New York

Johansson J, Liss L-E, Gullberg T, Björheden R (2006) Transport and handling of forest energy bundles—advantages and problems. Biomass Bioenergy 30:334–341

Johnson L, Lippke B, Oneil E (2012) Modeling biomass collection and woods processing life-cycle analysis. Forest Prod J 62:258–272

Klvac R, Ward S, Owende PMO, Lyons J (2003) Energy audit of wood harvesting systems. Scand J For Res 18:176–183

Kounina A, Margni M, Bayart J-B, Boulay A-M, Berger M, Bulle C, Frischknecht R, Koehler A, Motoshita M, Núñez M, Peters G, Pfister S, Ridoutt B, van Zelm R, Verones F, Humbert S (2013) Review of methods addressing freshwater use in life cycle inventory and impact assessment. Int J Life Cycle Assess 18:707–721

Laitila J (2008) Harvesting technology and the cost of fuel chips from early thinnings. Silva Fenn 42:267–283

Lindholm E-L, Berg S, Hansson P-A (2010) Energy efficiency and the environmental impact of harvesting stumps and logging residues. Eur J Forest Res 129:1223–1235

Lindholm E-L, Stendahl J, Berg S, Hansson P-A (2011) Greenhouse gas balance of harvesting stumps and logging residues for energy in Sweden. Scand J Forest Res 129:1223–1235

Mateus T (2007) O Potencial energético da floresta portuguesa: análise do potencial energético disponível para as centrais termoeléctricas a biomassa florestal lançadas a concurso. Faculdade de Engenharia da Universidade do Porto, Porto

Mattila T, Helin T, Antikainen R (2012) Land use indicators in life cycle assessment. Int J Life Cycle Assess 17:277–286

Mckechnie J, Colombo S, Chen J, Mabee W, Maclean HL (2011) Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels. Environ Sci Technol 45:789–795

MEI (2007) Renewable energy in Portugal. Ministério da Economia e da Inovação, Lisbon

Nunes JMSA (2008) Avaliação integrada da produção de electricidade com base em biomassa lenho-celulósica em Portugal: emissões de GEE, análise tecnológica e energética de ciclo de vida. Master Thesis. Universidade de Coimbra, Coimbra

Núñez-Regueira L, Proupín-Castiñeiras J, Rodríguez-Añon JA (2002) Energy evaluation of forest residues originated from *Eucalyptus globulus* Labill in Galicia. Bioresource Technol 82:5–13

Nuss P, Gardner KH, Jambeck JR (2013) Comparative life cycle assessment (LCA) of construction and demolition (C&D) derived biomass and US Northeast forest residuals gasification for electricity production. Environ Sci Technol 47:3463–3471

Pa A, Craven JS, Bi XT, Melin S, Sokhansanj S (2012) Environmental footprints of British Columbia wood pellets from a simplified life cycle analysis. Int J Life Cycle Assess 17:220–231

Roedl A (2010) Production and energetic utilization of wood from short rotation coppice—a life cycle assessment. Int J Life Cycle Assess 15:567–578

Silva MTC (2009) Análise do balanço entre sequestro e emissão de CO_2 resultante do circuito de produção e consumo de biomassa florestal numa central de co-geração. Master Thesis. Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, Lisbon

Tomé M, Oliveira T, Soares P (2006) O modelo Globulus 3.0—dados e equações. Publicações GIMREF—RC2/2006. Centro de Estudos Florestais do Instituto Superior de Agronomia, Lisbon

Valente CA, Sousa APM, Furtado FP, Carvalho AP (1992) Improvement program for *Eucalyptus globulus* at Portucel: technological component. Appita J 45:403–407

Valente C, Hillring BG, Solberg B (2011a) Bioenergy from mountain forest: a life cycle assessment of the Norwegian woody biomass supply chain. Scand J Forest Res 26:429–436

Valente C, Spinelli R, Hillring BG (2011b) LCA of environmental and socio-economic impacts related to wood energy production in alpine conditions: Valle di Fiemme (Italy). J Clean Prod 19:1931–1938

Valente C, Hillring BG, Solberg B (2012) Greenhouse gas emissions, energy use, and costs—case studies of wood fuel supply chains in Scandinavia. Int J Forest Eng 23:71–81

van Oers L, de Koning, Guinèe JB, Huppes G (2002) Abiotic resource depletion in LCA. Road and Hydraulic Engineering Institute, Ministry of Transport and Water, Amsterdam

Viana H, Cohen WB, Lopes D, Aranha J (2010) Assessment of forest biomass for use as energy. GIS-based analysis of geographical availability and locations of wood-fired power plants in Portugal. Appl Energy 87:2551–2560

Whittaker C, Mortimer N, Murphy R, Matthews R (2011) Energy and greenhouse gas balance of the use of forest residues for bioenergy production in the UK. Biomass Bioenergy 35:4581–4594

Wihersaari M (2005) Greenhouse gas emissions from final harvest fuel chip production in Finland. Biomass Bioenergy 28:435–443

Yoshioka T, Aruga K, Nitami T, Kobayashi H, Sakai H (2005) Energy and carbon dioxide (CO_2) balance of logging residues as alternative energy resources: system analysis on the method of a life cycle inventory (LCI) analysis. J For Res 10:125–134